8

Effective Cloud Properties for Large-Scale Models

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8.1 Introduction

The large-scale terrestrial climate is well-known to be sensitive to small changes in the average albedo of the earth-atmosphere system. Sensitivity estimates vary, but typically a 10% decrease in global albedo, with all other quantities held fixed, increases the global mean equilibrium surface temperature by 5°C, similar to the warming since the last ice age, or that expected from a doubling of CO_2 (e.g., Cahalan and Wiscombe, 1993). Yet not only is the global albedo of 0.31 only known to $\approx$ 10% accuracy[1] but current global climate models often do not predict the albedo in each gridbox from realistic cloud liquid water distributions; they normally tune the liquid until plane-parallel radiative computations produce what are believed to be typical observed albedos. The inability of global climate models to compute the

[1] Estimates of global albedo range from 0.30 to 0.33, or 3 out of 31 $\approx$ 10%, (e.g., Kiehl and Trenberth, 1997).

albedo is due to their inability to predict the microphysical and macrophysical properties of cloud liquid water within each gridbox, and their reliance on plane-parallel radiative codes. As Stephens (1985) has emphasized, the mean albedo of each gridbox depends not only on the mean properties of clouds within each box, but also upon the variability of the clouds, which involves not only the fractional area covered by clouds, but also the cloud structure itself. During recent years many climate models began to carry liquid water as a prognostic variable, e.g., Sundqvist et al. (1989) and Tiedtke (1996). It is important to treat cloud radiation and cloud hydrology consistently, which requires that cloud parameterizations become dependent on the fractal structure of clouds. Radiative properties of singular multifractal clouds have been previously studied (e.g., Cahalan, 1989; Cahalan and Snider, 1989; Lovejoy et al., 1990; Gabriel et al., 1990; Davis et al., 1990). Here we shall show how radiative properties of marine stratocumulus boundary-layer clouds, and specifically area-average albedo of these clouds, depend on their structure. The central role of this cloud type in maintaining the current climate was clarified and quantified in Ramanathan et al. (1989).

The dependence of average albedo on cloud structure has been found to be especially important in the case of marine stratocumulus, a major contributor to net cloud radiative forcing. Computations based on observations of California stratocumulus during the First International Satellite Cloud Climatology Project (ISCCP) Regional Experiment (FIRE) have shown that stratocumulus have significant fractal structure, and that this "within-cloud" structure can have a greater impact on average albedo than cloud fraction (Cahalan and Snider, 1989; Cahalan et al., 1994b,a). These studies employed a "bounded cascade" model to distribute the cloud liquid, defined in terms of two cascade parameters: f, the difference in cloud liquid fractions between two segments of the full cloudy domain being considered, and c, the difference of liquid fractions at the next smaller scale (within each segment) divided by f.[2] Parameters c and f are empirically adjusted to fit the scaling exponent of the power spectrum of liquid water path (W), $\beta(c) \approx 5/3$, and the standard deviation of $\log W$, $\sigma(f)$, respectively. In order to isolate the effects of horizontal liquid water variations on cloud albedo, it is convenient to assume that the usual microphysical parameters are homogeneous, as is the geometrical cloud thickness. In order to simplify comparison with plane-parallel clouds, the area-averaged vertical optical depth is kept fixed at each step of the cascade. The albedo bias is then found as an analytic function of the fractal parameter, f, as well as the mean vertical optical thickness, τ_v, and sun angle, θ_0. For the diurnal mean of the values observed in FIRE ($f \approx 0.5$, $\tau_v \approx 15$, and $\theta_0 \approx 60°$) the absolute bias is approximately 0.09, nearly 15% of the plane-parallel albedo of 0.69. Diurnal and seasonal variations of cloud albedo bias have been determined from observations during the Atlantic Stratocumulus Transition Experiment (ASTEX) and compared to the FIRE results (Cahalan et al., 1995).

[2] Bounded cascades were first introduced in Cahalan et al. (1990), and their scaling properties studied in Marshak et al. (1994). For a description of bounded cascades in terms of f and c, see the discussion following (8.2) below.

The goal of this chapter is to show how these results for the mean albedo of bounded cascade clouds, derived in the references cited above, may be applied to parameterizing the albedo of such clouds in terms of the plane-parallel albedo of a cloud having an "effective optical thickness" which is reduced from the mean thickness by a factor $\chi(f)$ which depends only on the fractal parameter f, or equivalently $\sigma(f)$, and not on the mean cloud properties. This "effective thickness approximation" (ETA) is a special case of the more general "independent pixel approximation" (IPA), sometimes referred to as the "independent column approximation" (ICA) especially for gridded climate models. The key assumption of any IPA (or ICA) type approximation is the neglect of horizontal photon transport (see Chap. 12). In addition, it depends only on 1-point cloud probability distributions, not on the spatial arrangement or correlations of individual cloud elements. On the other hand, knowledge of the *accuracy* of any IPA approximation depends on three-dimensional (3D) radiative transfer (i.e., with net horizontal fluxes) as well as on the spatial (typically fractal) cloud structure. In this chapter, though we compare the IPA/ICA with 3D radiative transfer as is done in other chapters, the primary purpose is to compare the IPA with the much simpler ETA. In particular, we use a simple fractal "bounded cascade" model to (1) motivate the ETA; and (2) determine the accuracy of the ETA by comparing it to the full IPA, using cloud parameters typical of marine stratocumulus. Moreover, some analytic results for bounded cascades are generalized and simplified in two appendices. In the "Further Readings" section at the end, we point the reader to simple alternatives to the ETA, each of which have particular advantages and points of view. We feel that each approximation is helpful insofar as it lends some insight into real clouds, which are far more complex than any of our mathematical idealizations, as anyone can discover who takes the opportunity to study the amazing variety of real cloud systems.

In the following, we first define some terms in Sect. 8.2. Then Sect. 8.3 shows that the IPA provides estimates of the plane-parallel albedo bias accurate to about 1% for bounded cascade clouds, and Sect. 8.4 applies the IPA to show that the total absolute bias reaches a maximum of about 0.10 during the morning hours, when the cloud fraction is nearly 100%. These two sections are primarily summaries of results from Cahalan et al. (1994b) and Cahalan et al. (1994a), although there a 1D cascade was employed, while a here a 2D cascade is applied. Section 8.5 gives the main result, that under certain commonly-observed conditions the albedo is approximately the plane-parallel albedo at a reduced "effective optical thickness" $\tau_{\mathrm{eff}} \equiv \chi\tau_{\mathrm{v}}$, where the reduction factor χ decreases with f, or equivalently $\sigma(f)$, approximately as $10^{-1.15\sigma^2}$ (see Fig. 8.5 and (8.B.12)), independently of the mean vertical optical depth, τ_{v}. The accuracy of this approximation is given as a function of both f and the mean thickness. The results are summarized and their limitations briefly discussed in Sect. 8.6. Appendix 8.A shows that all moments of a bounded cascade may be obtained by considering only the second moment as a function of the fractal parameter. This generalizes expressions for the second and third moments given in Cahalan et al. (1994a), and allows the lognormal behavior in the singular limit to be explicitly exhibited (see also Cahalan, 1994). Appendix 8.B gives expressions for $\chi(f)$

and $\sigma(f)$ as power series in f with coefficients depending on c, and evaluates the coefficients for the case of a $\beta(c) \approx 5/3$ wavenumber spectrum.

8.2 Definitions

Many general circulation models (GCMs) are now predicting mean cloud liquid water in each gridbox, not merely diagnosing it from other quantities. The cloud albedo could potentially also be accurately predicted, if cloud liquid could be accurately distributed within each gridbox. Efforts are underway to improve the treatment of cloud distributions in global models, so that simulated clouds can respond more realistically to climate change. The hope is that average cloud liquid in each gridbox will be accurately predicted, and that the resulting cloud albedo will be correctly computed from this, and other average cloud parameters. It is important to recognize, however, that *mean cloud parameters are insufficient* to compute the mean albedo. The mean albedo also depends, at a minimum, on the deviations of the liquid water from the mean, for instance, on the mean *and standard deviation* of the logarithm of the liquid water. We demonstrate this here and in the next using the bounded cascade model.

The schematic in Fig. 8.2 shows three approaches to distributing a prescribed amount of liquid water in a given vertical level of a GCM gridbox. In (a) it is uniform over the whole area, and thus the albedo may be computed from plane-parallel theory, and depends only on the *average* optical thickness, effective particle radius, and so on. In (b) the cloud is assumed to cover only a fraction of the area, is somewhat thicker in order to contain the same total liquid, but is still assumed to be uniform on that so-called “cloud fraction.” In this case the mean albedo of the gridbox is assumed to equal the area-weighted average of a “cloud albedo” and a “clear-sky” albedo. Finally, in (c) the cloud covers the same cloud fraction as in (b), with the same mean parameters, but is assumed to have a non-uniform structure which depends on one or more “fractal parameters.” The cloud fraction and the fractal parameters are assumed to depend on geographic region, season, and time of day.

As a measure of the impact of cloud fraction and fractal parameters on the average albedo, we define the “absolute plane-parallel albedo bias” ΔR_{pp}, as the mean albedo computed in case (a) minus that in case (c). This may be expressed symbolically as:

$$\Delta R_{\mathrm{pp}} = R_{\mathrm{pp}} - [A_{\mathrm{c}} R_{\mathrm{f}} + (1 - A_{\mathrm{c}}) R_{\mathrm{s}}], \tag{8.1}$$

where R_{pp} is the plane-parallel reflectivity, R_{f} is the mean reflectivity of the fractal cloud, R_{s} is the mean clear-sky reflectivity, and the same total liquid water is used in all cases. The *relative* plane-parallel albedo bias is the absolute bias divided by R_{pp}. To avoid confusion, the absolute bias is always given as a fraction, while the relative bias is given in percent. Since the simple uniform cloud fraction model shown in Fig. 8.2b is currently widely employed, it is convenient to split the total plane-parallel bias into the difference between (a) and (b), plus the difference between (b) and (c). Symbolically: